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Structured wire: From single wire experiments to multi-crystalline silicon wafer mass production

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ABSTRACT

This work presents the evolution from fundamental single wire sawing experiments using structured wire for the first time to the introduction of this wire in multi-crystalline silicon wafer mass production. It is shown that via single wire experiments 100% higher throughput and more than 10% less specific energy consumption were foreseen for the replacement of straight with structured wire in mass production of multi-crystalline silicon wafers. The analysis of production data demonstrates that these predictions were even exceeded and that additionally, 45% less wire consumption and 40% less slurry consumption were achieved. This work reveals the influence on wafer metrology and gives a basic description of the dynamics in the cutting slot.

1. Introduction

The entire solar industry is heading for the main goal to minimize the cost per Wattpeak for PV-systems. Hence, the industry is reducing the production cost along the manufacturing chain on the one hand and is increasing the efficiencies of photovoltaic systems on the other hand. Within the wafering part of the value chain for crystalline silicon based solar cells beside many ideas of kerfless wafering [1–3] or direct solidification [4–6] a main and straight forward goal is to decrease the consumption of consumables, which are sawing wire (straight, structured, diamond-bonded) and abrasive slurry as the major cost drivers. Reducing cost in the production of multi-crystalline silicon wafers, two approaches are intensively discussed within the R&D wire sawing community: diamond wire (fixed abrasive process) [7–10] and slurry-based process (loose abrasive process) [11–14].

Beside all the promising work done on diamond wire, newly structured wire was developed by wire suppliers in order to lead the slurry-based multi-wire sawing process to high efficient performances and lower cost, at least for cutting multi-crystalline silicon wafers [14,15].

Structured wire was introduced in sawing applications for bricketing (squaring) of large G4-G5 multi-crystalline or mono-crystalline silicon ingots several years ago. Without structured wire, those wire sawing operations had faced a drying out of slurry at the wire exit of the cutting slots. Large diameter structured wire did solve the problem by keeping the slurry all along with the wire in the slot. These advantages were subject of further research and development of structured sawing wires with diameters comparable to the straight wire used in slurry-based multi-wire sawing technique (see example of structured wire in Fig. 1) [14,15]. Nowadays, challenges with the structured wire like breakage, high kerf loss and less cutting performance were overcome and structured wire was introduced into wafer mass production at PV Crystalox Solar Silicon GmbH in Erfurt, Germany to substitute the straight wire by 100%. Since then, development of cost effective sawing processes continued and conducted scientifically. This work presents the differences between structured and standard straight wire process and gives a basic explanation on the dynamics in the cutting slot based on experiments using a single wire setup [16,17].

2. Material and methods

2.1. Single wire experiments

2.1.1. Experimental setup

A standard HCT E300 wire saw was set up as already described in [16] for the experiments. The wire web was separated to isolate a single wire to obtain a single slot in a small silicon brick (see Fig. 2). The temperature of the silicon block was monitored using thermocouples PT100. An extra slurry tank provided temperature controlled slurry with F800 silicon carbide (SiC) grains as abrasives and PEG200 as carrier at 22–23 °C. The slurry was pumped with a

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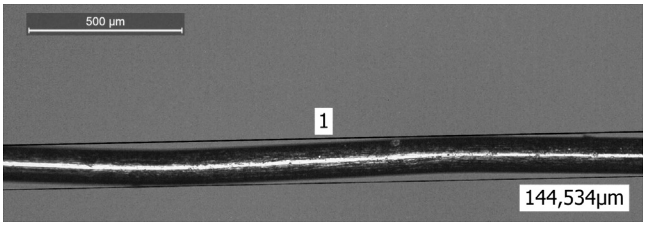

Fig. 1. Picture of structured wire taken by light microscopy shows bent structure and "outer diameter".

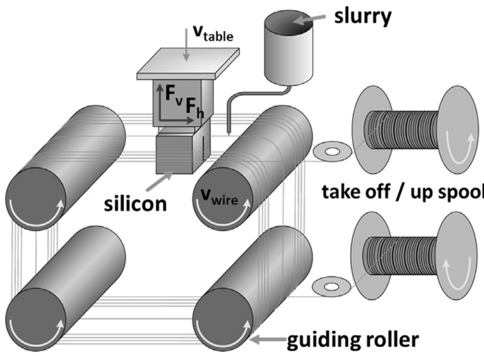

Fig. 2. Schematic view of the single wire setup wire web, position of the force measurement (F_v and F_h) at the silicon block.

constant flow rate of 500 ml/min directly onto the moving wire and the slurry temperature was controlled by a thermocouple PT100 at the slurry supply.

2.1.2. Set of experiments

Two sets of experiments were performed using a) straight wire with a diameter of 120 µm and b) structured wire with a diameter of 115 µm and an apparent "outer" diameter ranging from 120 to 160 µm. Six mono-crystalline silicon blocks with varying lengths of 25, 50, 100, 150, 200 and 230 mm were cut consecutively with each wire. For all 2×6 sets constant cutting conditions with 7 m/s wire speed, 200 µm/min table speed and 20 N wire tension force were chosen. Two strain gauges were placed between table and silicon block to measure the horizontal (F_h) and vertical forces (F_v) that take effect at the silicon block during the sawing process (see Fig. 2). The horizontal force is parallel to the moving wire and works against the wire speed while cutting. It is an indication of the power consumption of a wire saw, since the majority of power is used to shear the viscous slurry between fast moving wire and silicon block walls in the cutting slot. The vertical force is parallel to the table drive direction and occurs when the silicon block is forced against the wire. The vertical force is an indication of the "cutting performance": the lower the vertical force the higher the "cutting performance" [12,17]. Both forces can be measured without major influence on one another. The measurements of horizontal and vertical forces that are working on the silicon block during the sawing process were taken into account while reaching steady state conditions, where the table forward speed equals the vertical speed the wire is cutting through the silicon block with.

2.1.3. Sample preparation and microscopic measurements

After each cut the respective silicon block was prepared to obtain two plates with thicknesses of a few millimeters: one plate from the wire entry side and one from the wire exit side (see Fig. 3). These plates were used for the measurement of the two slot width originating from straight and structured wire, using an optical microscope Leica DM6000M. The total slot width variation, which equates the total thickness variation (TTV) of the resulting wafers, was calculated using the microscopic measurements.

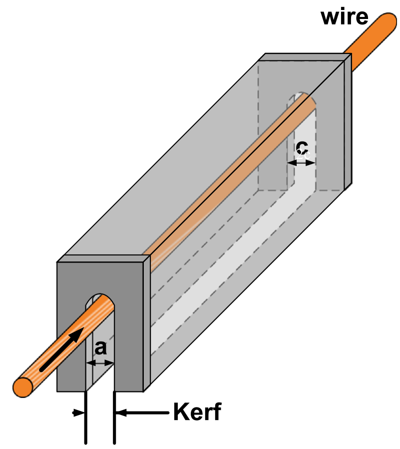

Fig. 3. Sketch of a silicon block cut with one wire. Prepared plates at the wire entry with slot width (a) and the wire exit with slot width (c) are highlighted.

2.1.4. Roughness measurements

The 230 mm block was analyzed regarding the surface roughness according to DIN EN ISO 4288 [18] and 4287:1998 [19] at twelve positions between wire entry and exit with a perthometer M1 (Mahr). The parameters were set to a measured length of L1 = 5.6 mm, a cutoff of $\lambda_0 = 0.8$ mm and a number of discrete measurement paths $n = 7 - 2$. For each measured position the arithmetic mean value, R_a, was determined.

2.2. Mass production

Over 4000 cuts with structured wire were performed in mass production using a standard industrial wire saw type Meyer Burger DS 262 and DS 271 in order to produce multi-crystalline silicon wafers with a dimension of $156.0 \times 156.0 \times 0.2$ mm. The average block length per cut was 900 mm. The same slurry composition was used as during the single wire experiments. Over a period of one year, table forward speeds were increased and slurry consumption was decreased. Each set of wire sawing parameters was rated as successful, when more than 40 cuts were performed with standard production sawing yields. As a basis for a percentaged comparison, cuts with straight wire and the same slurry were taken into account, which were performed right before the introduction of structured wire.

2.2.1. Energy consumption measurements

In order to determine the energy consumption in kW the recorded process data of a Meyer Burger DS271 wire saw before (straight wire process) and after the introduction of structured wire were used. The specific energy consumption was calculated using the average power consumption of the wire sawing machine and the silicon contact length of the specific cut (number of wire windings times 156 mm wafer side length).

2.2.2. Wafer thickness measurements

In order to determine the center thickness of each wafer a standard industrial Hennecke measurement system with inductive thickness sensors was used. One single cut using a Meyer Burger DS 271 with a constant pitch of wire guiding roller grooves of 345 µm was chosen to present the center thicknesses of wafers.